IJE TRANSACTIONS B: Applications Vol. 28, No. 2, (February 2015) 251-260

International Journal of Engineering

Journal Homepage: www.ije.ir

An Experimental and Theoretical Study of the Effects of Excess Air Ratio and Waste Gate Opening Pressure Threshold on Nox Emission and Performance in a Turbocharged CNG SI Engine

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PAPER INFO

Paper history:
Received 06July 2014
Received in revised form 07November2014
Accepted 13November2014

Keywords:
Turbocharged CNG SI Engine
NOx Emission
Performance
ECE-R49 Test Cycle
Excess Air Ratio
Waste Gated Turbocharger

ABSTRACT

In this research, effects of excess air ratio and waste gate opening pressure threshold on NOx emission and performance in a turbocharged CNG SI engine are experimentally studied at 13-mode ECE-R49 test cycle. The engine power, boost ratio and charge air temperature are investigated experimentally at the cycle for different waste gate pressure thresholds. A code is developed in MATLAB environment for predicting engine performance and NOx and the results are validated with the research experiments. The effects of excess air ratio on the engine indicated power and specific fuel consumption as well as NOx emission are numerically investigated at WOT by the code. NOx emission of WOT is max at excess air ratio of 1.1. Simulation reveals that higher excess air ratio at a rate of 20% decreases maximum indicated power 9% and improves minimum ISFC 7%. Experiments indicate that brake power augments with increase of the pressure threshold especially at high loads and speeds due to higher boost ratio. It is also found that changing the threshold from 165mmHg to 200 and 265mmHg decreases total bsNOx at rate of 6 and 12%, respectively. The threshold increase to 323mmHg augments total bsNOx. Therefore, the threshold of 265mmHg is optimum threshold among the four pressure thresholds experimented.

***doi**: 10.5829/idosi.ije.2015.28.02b.11*

NOMENCLATURE

bsNOx	brake specific NOx emission	rpm	revolutions per minute
bTDC	before top dead center	rg_{Vol}	total EGR volumetric fraction
c	flame speed parameter f(Tu, ϕ)	RON	research octane no.
CA	crank angle	S_L	laminar flame speed
CI	compression ignition	S_T	turbulent flame speed
CNG	compressed natural gas	SCR	selective catalyst reduction
d	flame speed parameter f(Tu, ϕ)	SI	spark ignition
DI	direct injection	SIM	simulated
ECE	economic commission for Europe	ST	spark timing
EGR	exhaust gas recirculation	T_u	unburned mixture temperature
EXP	experimental	T	temperature (K) or (°C)
HCNG	hydrogen and CNG blend	TDC	top dead center
IMEP	indicated mean effective pressure	Tot.	Total
ISFC	indicated specific fuel consumption	Total bsNOx	brake specific NOx of the ECE-R49 cycle totally
IVC	intake valve close	u'	turbulence intensity
k	turbulent kinetic energy	WOT	wide open throttle
l_i	turbulence integral length scale	W-G O. P. T.	waste gate opening pressure threshold
PM	particulate matter	**Greek Symbols**	
PN	particulate number	λ	excess air ratio

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Please cite this article as:Sh. Kharazmi, A. H. Benisi, A.Mozafari, An Experimental and Theoretical Study of the Effects of Excess Air Ratio and Waste Gate Opening Pressure Threshold on Nox Emission and Performance in a Turbocharged CNG SI Engine, International Journal of Engineering (IJE), TRANSACTIONS B: Applications Vol. 28, No. 2, (February 2015) 251-260

N	engine speed (rpm)	μ	unburned mixture dynamic viscosity
NMHC	non-methane hydrocarbon	ρ_u	unburned mixture density
NOx	nitric oxides	ϕ	fuel/air equivalence ratio
P_b	brake power (kW)	**Subscripts**	
pcyl	cylinder pressure (bar)	cyl.	cylinder
ppm	part per million	L	laminar
Rel.	Relative	T	turbulent
Re_T	turbulent Reynolds number $= l_I u' \rho_u / \mu$	u	Unburned

1. INTRODUCTION

The conventional fuels that are main energy sources of the internal combustion engines are gasoline and Diesel fuels. Availability, competitive price and high energy density are main advantages of the conventional fuels. Natural gas, as an alternative fuel, has proven R/P (reserve to production ratio) of 60 years in comparison with 40 years for crude oil [1].

Natural gas is mainly composed of methane with higher molar H/C ratio of 3.8 as compared with ratios between 1.8 and 2.0 for gasoline and Diesel fuels. The higher H/C ratio decreases CO_2 emission, and therefore its green-house effects. Natural gas engines produce about 20% lessCO_2than gasoline engines for the same power[2]. Spark ignition natural gas engines have the potential to produce much lower CO, CO_2 and THC emissions as compared with gasoline engine. These engines also have significantly lower THC and PM emissions in comparison with Diesel engine [3].

Natural gas possesses relatively wider flammability limits, with better combustion stability in lean-burn strategies. Its higher research octane number (RON) also allows higher compression ratio that leads to higher fuel consumption efficiencies. On the other hand, natural gas reduces engine volumetric efficiency due to its injection in intake manifold (in comparison with Diesel fuel) and its lower stoichiometric fuel/air ratio (compared to gasoline) that leads to less power output. Turbocharger can offset this power decrease. Stoichiometric fuel/air ratio of Natural gas is lower than those of gasoline and Diesel fuels due to its higher H/C ratio. It exploits exhaust gas energy to compress intake air; therefore, more fuel can be burned in a cycle. Turbocharging of SI engines has been improved less than Diesel engines due to many difficulties, such as knock and turbocharger matching [4-6].

Korakianitis et al. [1]extensively reviewed CI and SI natural gas engines. The engine performance, combustion characteristics and emission levels were assessed. They found that emission generation characteristics of pure natural gas engines are not well-known. Cho and He [7] reviewed SI natural gas engines. They concluded that high activity catalyst for methane oxidation and lean de-NOx system or three-way catalyst with precise fuel/air ratio control strategies should be developed to meet strict emission standards.

Kharazmi et al. [2] presented and discussed WOT performance and emission characteristics of present research turbocharged natural gas SI engine theoretically as well as experimentally. They found that waste-gated turbocharger substantially affects WOT brake torque and results in better torque back-up.

Ibrahim and Bari [8] experimentally investigated the effects of stoichiometric air-fuel mixture with exhaust gas recirculation (EGR) technique on performance and NOx emission of a SI natural gas engine for both atmospheric and supercharged inlet conditions. It was found that EGR had a significant effect on NOx emissions. They [9] also compared the effects of EGR with lean-burn on natural gas SI engine performance at similar operating conditions. It was concluded that EGR dilution strategy was capable of producing extremely lower NOx emission than lean-burn technique. NOx emission reduced about 70% when the inlet charge was diluted at a rate of 20% using EGR instead of excess air. ECE-R49 is a 13-mode steady-state engine test cycle introduced by ECE Regulation No. 49. It has been used for type approval emission testing of heavy-duty engines through emission standards. The test cycle is performed on an engine dynamometer through a sequence of 13 load and speed conditions i.e. modes. Exhaust emissions measured at each mode are stated in g/kWh. The final test result is a weighted average of the 13 modes. The test conditions and weighting factors of the cycle are shown inFigure 1. The areas of circles in the graph are proportional to the weighting factors for the respective modes [1].

Mohebbi et al. [10]experimentally studied the effects of EGR distribution on the combustion, emissions and performance in a turbocharged DI Diesel engine. The results revealed that the increase of EGR rate caused the reduction of NOx emission due to the decrease in peak cylinder pressure and flame temperature. Jafarmadar and Pashae [11] carried out experiments on semi-heavy duty agricultural DI Diesel engine at various loads in order to evaluate its performance and emissions using the blends of Diesel fuel with different volumetric

http://www.dieselnet.com/standards/cycles/ece_r49.php1.accessed Oct. 2014.

fraction of castor oil and pure Diesel fuel separately. They found that 15% volumetric castor oil increased NOx emission by 4% at 50% load. However NOx emission augments by 9% at 30% volumetric castor oil and 25% load. Ebrahimi and Mercier [12] carried out experiments adjusting the spark timing to the maximum brake torque timing in various equivalence ratios and engine speeds for gasoline and natural gas operations. The results revealed that over the entire range of engine speed and equivalence ratio, the exhaust gas temperature and the lubricating oil temperature for gasoline operation is higher than that of natural gas operation, while the exhaust valve seat temperature for natural gas operation is higher.

Emission standards become stricter in future [13]. The NOx emission has been the strictest Euro emission standard for CNG buses, with a limit of 0.46 g/kWh in Euro VI standard [2].

NOx emission of natural gas engines is high, especially when turbocharger is used to offset their power reduction. 3-way catalyst and SCR techniques are expensive, occupy engine compartment, need a certain exhaust gas temperature range and add some complexity to the engine use. Emission generation characteristics of pure natural gas engines especially at lean-burn strategy are not well-known [1]. There is little literature about the effects of waste-gate on engine performance and especially its emissions. In the present research, the effects of excess air ratio on indicated power and specific fuel consumption of a turbocharged CNGSI engine is investigated under WOT by simulation. The effects of excess air ratio on the engine NOx emission are also investigated experimentally under 13-mode ECE-R49 test cycle Moreover, as an excellent innovation, waste-gate opening pressure threshold is also changed to assess its effects on the engine power, boost ratio, charge air temperature and NOx emission as well as bsNOx and total bsNOx under the test cycle, experimentally.

2. ENGINESPECIFICATIONS AND EXPERIMENTAL SETUP

Experiments have important role in the internal combustion research fields. Engine specifications, experimental setup including measuring instruments as well as experimental procedures are presented in this section.

2. 1. Engine Specifications The engine was a turbocharged Diesel-base CNG engine. The engine had previously been turbocharged at Sharif University turbocharging lab. The main engine specifications are summarized in Table 1.

2. 2. Experimental Setup The experiments were carried out at the turbocharging lab of Sharif University of Technology (SUT).;Figure2 shows its schematic. The test bed was equipped with an eddy current dynamometer with measurement accuracies of ±1 Nm and ±1 rpm for the torque and engine speed, respectively. Ambient temperature and engine charge air temperature at aftercooler exit were measured by J-type thermocouples. Ambient pressure as well as boost pressure was measured within accuracy of ±136 Pa (1 mmHg). The engine on the test bed is shown in Figure 3.

Since the engine was turbocharged, it was possible to use a bellmouth air flow meter [14], with throat diameter of 3 inch (76.2 mm). Differential static pressure of the bellmouth throat and ambient was measured with an accuracy of ±10 Pa[2].AVL exhaust gas analyzer of DiCom 4000 was used to measure exhaust gas composition. Volumetric (or mole) fraction of NOx was measured as well as excess air ratio [3].

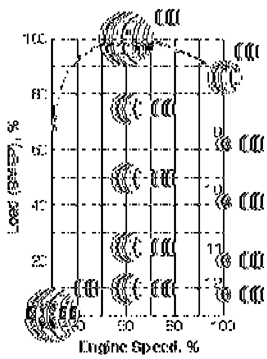

Figure 1. ECE-R49 test Cycle [2].

TABLE 1. The test engine main specifications[2].

No. and arrangement of cylinders	6 in line
Displacement volume	11.58 liter
Stroke	128 mm
Bore	150 mm
Connecting rod length	280 mm
Compression ratio	10.5:1
Number of valves	2 inlet and 2 outlet
Turbocharger	Twin-entry waste gated water-cooled CNG Schweitzer S300G
Firing order	1-5-3-6-2-4
Fuel delivery system	Carburetor/Mixer

http://www.dieselnet.com/standards/cycles/ece_r49.php2.accessed Oct. 2014.

3. AVL, Operational Manual, Engine diagnostics AVL DiCom 4000, (2001)

Spark timing was measured by AVL timing light. Engine cylinder pressure variation with crank angle was also measured by Kistler 6118B spark plug piezoelectric pressure transducer, CA encoder 2614A and TDC sensor of 2629B type. The measurement accuracies are listed in TABLE 2.

2. 3. Experiments Experiments were performed in steady state condition under 13-mode ECE-R49 test cycle at four different waste gate opening pressure thresholds by adjusting length of actuator rod. Decreasing length of the adjustable actuator rod increases the exerted force to the valve of waste gate; consequently the opening range of waste gate decreases i.e. the opening pressure threshold of waste gate increases. The adjusted pressure thresholds were 165, 200, 265 and 323 all in mmHg. Experiments were also performed at four different excess air ratios of 1.22, 1.29, 1.52 and 1.73 under the test cycle. ECE-R49 test cycle including multi-mode steady state tests that each mode has a special speed and load together with a specific weighting factor as indicated inFigure 1. Cylinder pressure variation with crank angle, and TDC position were measured and pegged for the code validation. NOx emission and boost ratio were also measured at WOT operating condition for the code calibration.

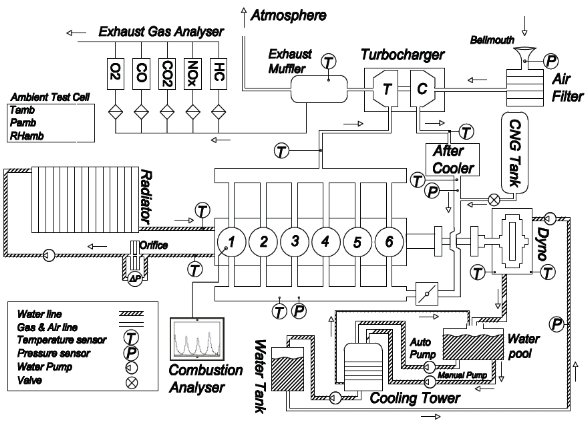

Figure 2. Schematic of turbocharging lab at Sharif University of Tech.

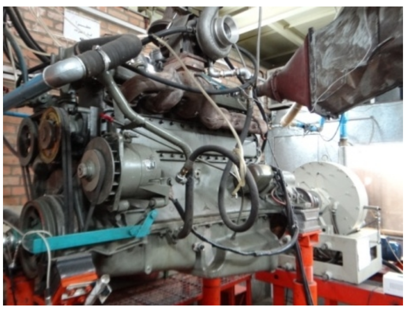

Figure 3. Experimental turbocharged CNG engine on test bed.

TABLE 2. Accuracies of the measurements.

Measurement	Accuracy
Power	±1 %
Engine speed	±1 rpm
Temperature	±1 K
Pressure	± 136 Pa
Differential pressure	± 10 Pa
NOx emission	±1 ppm by vol.
Spark timing	±0.1 °CA

3. MODELING

In order to complete experiments and save time and money, engine simulation model is developed. The engine simulation model is a quasi-dimensional two-zone model for describing dynamic behavior during the compression, combustion and expansion strokes. By using experimental inlet air temperature and boost pressure, an estimation of data for the first step of compression process is obtained and engine air consumption is validated with corresponding experimental results. First law of thermodynamic is satisfied for each step of cycle calculation. A hemispherical flame front propagates from spark plug located at the center of combustion chamber cylinder head. Flame front propagation and intersection with Mexican-hat bowl of piston and cylinder liner are precisely calculated based on complete combustion chamber geometry. Heat loss from cylinder contents to its surrounding surfaces is calculated by Hohenberg semi-empirical relation [15], the most appropriate relation for CNG engines [16].

3. 1. Turbulence Simulation The turbulence model is built up using mean values (averaged over the entire combustion chamber volume) with no differentiation between unburned and burned zones. Turbulent kinetic energy (TKE) at the time of intake valve close (IVC) is assumed to be 20% of the intake flow mean velocity squared [4]. There are 3 terms in $k-\varepsilon$ equation which are related to TKE dissipation and TKE production due to compression and squish[2]:

$$\frac{dk}{dt}=\left(\frac{dk_{comp}}{dt}\right)+\left(\frac{dk_{squish}}{dt}\right)-\left(\frac{dk_{diss}}{dt}\right) \quad (1)$$

Turbulence intensity u' is calculated from TKE[2]. Turbulence integral length scale is obtained from mass conservation of eddy[4].

3. 2. Laminar Flame Speed It is quoted by Lammle [17] that Witt and Griebel proposed methane laminar flame speed relation considering special turbocharged combustion conditions i.e. higher unburned mixture temperature. Witt and Griebel relation is valid for unburned temperatures up to 850 K; while those of others [18-20] are valid for up to 550 K and extend for up to 650 K at most [21]. EGR effects on CNG laminar flame speed are considered by experimental relation proposed by Liao [19]. Therefore, the laminar flame speed is in the form of Equation (2) for mixture of methane and air containing EGR [2]:

$$S_L = c.\,p_{cyl}^{-d}(4.4825\,rg_{vol}^2 - 4.1988\,rg_{vol} + 0.9952) \quad (2)$$

3. 3. Turbulent Flame Speed Gulder [22] proposed the ratio of premixed turbulent flame speed to laminar flame speed for wrinkled regime of engine combustion using methane flame experimental results as below [2]:

$$\frac{S_T}{S_L} = 1 + 0.62(\frac{u'}{S_L})^{1/2}\, Re_T^{1/4} \quad (3)$$

3. 4. NOx Formation Kinetic Model The thermal or extended Zeldovich mechanism [23] is applied to determine the rate of change of NO concentration during combustion and expansion processes as follows:

$$\frac{d[NO]}{dt} = \frac{2R_1\{1-([NO]/[NO]_e)^2\}}{1+([NO]/[NO]_e)R_1/(R_2+R_3)} \quad (4)$$

where

$$R_1 = k_1^+[N_2]_e[O]_e = k_1^-[NO]_e[N]_e \quad (5)$$

$$R_2 = k_2^+[N]_e[O_2]_e = k_2^-[NO]_e[O]_e \quad (6)$$

$$R_3 = k_3^+[N]_e[OH]_e = k_3^-[NO]_e[H]_e \quad (7)$$

where sign [ ] denotes concentration, and subscript e refers to equilibrium value. The rate constants k1, k2 and k3 are calculated from GRI-MECH 3.0 in units of m3/ (kmol.s) [4]. NOx kinetic model uses multi-zone in burned mixture related to each crank angle degree. Equilibrium concentration is used from combustion simulation results.

4. MODEL VALIDATION

The presented model was validated according to the experimental results of the in-cylinder pressure and NOx emission of the turbocharged CNG SI engine with specifications shown in Figure 4.

4.Smith GP, Golden DM, Frenklach M, et al., http://www.me.berkeley.edu/gri_mech/ accessed 22nd Jun. 2014

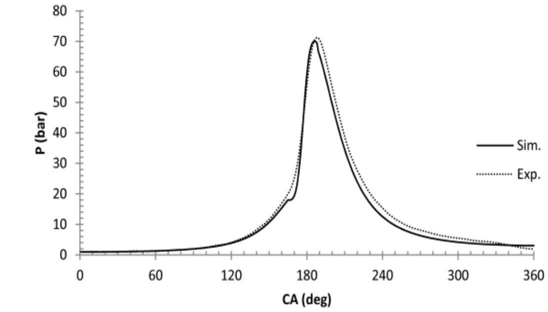

Figure 4. A comparison between experimental and simulated in-cylinder pressure variation of the engine at 800 rpm, part load, spark timing of 25obTDC and λ of 1.25.

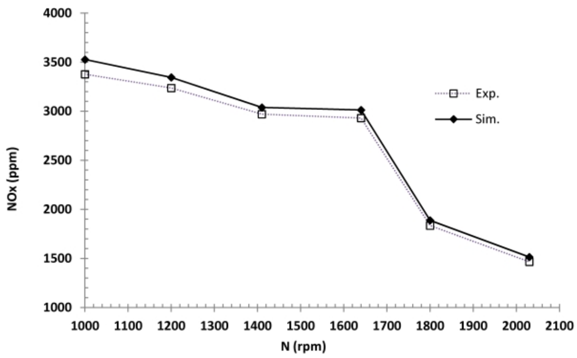

Figure 5. A comparison between simulated and experimental NOx emission of the engine at WOT, λ of 1.234 and spark timing of 25obTDC.

Figure 4 compares the simulated results with present experimental results of in-cylinder pressure at 800 rpm, part load, excess air ratio (λ) of 1.25, spark timing of 25obTDC with no EGR consideration. There is a good agreement between simulated and experimental results. The validation has been discussed in detail[4].The area below the pressure versus crank angle is equal to the indicated power. Therefore, indicated power is validated. The adjusted experimental magnitude of pressure and temperature of charge air is used for validation, so that charge air flow rate is also validated. Considering the experimental excess air ratio being used in the code, consequently fuel consumption as well as ISFC is corroborated for parametric study.

Figure 5 shows a comparison of simulated results with present experimental results for NOx emission. Since there is a strong non-linear dependency of the NOx formation on the burned gas temperature, the value of simulated NOx emission was calibrated to the experimental data level. This calibration is of high importance concerning the general validity of the NOx model. Even with a restricted application of certain combustion concepts, very useful results can be obtained [24].

5. RESULTS AND DISCUSSIONS

Excess air ratio effects were investigated on the engine indicated power and specific fuel consumption as a parametric study by the code at WOT operating condition. The engine was also experimentally investigated under 13-mode ECE-R49 test cycle and the effects of excess air ratio on NOx emission and power were assessed and discussed. The engine boost ratio, charge air temperature, brake power, NOx emission, bsNOx and total bsNOx were also experimentally investigated by changing the waste gate opening pressure threshold under the test cycle.

5. 1. Parametric Study of Excess Air Ratio The validated code has been used to study the effects of excess air ratio on indicated power and ISFC.Figure 6 shows the effects of the increase of excess air ratio on variation of indicated power with engine speed. The indicated power decreased with increase of excess air ratio as air replaced some of the inlet fuel mass. Increase of excess air ratio at a rate of 20% decreased maximum indicated power 9%. Higher excess air ratio reduced flame speed and slowed down the combustion rate significantly. The extended combustion duration resulted in burning most of the fuel away from TDC which caused a loss in indicated power at higher excess air.

Figure 7 gives the effect of excess air ratio increase on variation of indicated specific fuel consumption (ISFC) with engine speed. Indicated fuel economy wasimproved by leaner operation. Minimum ISFC decreased 7% with increase of excess air ratio at a rate of 20%. Burned gas temperature decreased with increase of excess air ratio, leading to lower heat losses to cylinder walls, and consequently lower ISFC. However, at higher excess air ratios, flame speed decreased and created drivability problems and at most, partial burning of the charge. Another effect of lean operation is the lower exhaust gas temperature which is of high importance for the efficiency and light-off temperature of catalyst, if it is available. Engine durability and cost improve with increase of excess air ratio.

Kharazmi et al. [2] have previously found that NOx emission of the engine at WOT increased as excess air ratio augmented from stoichiometric value up to NOx peak value at excess air ratio of 1.1 due to higher available oxygen concentration. The NOx emission decreased when excess air ratio increases above 1.1 since the burned gas temperature reduced.

5. 2. Experimental Study of Excess Air Ratio Figure 8 shows variation of experimental NOx emission with different 13 modes of ECE-R49 test cycle at four excess air ratios.

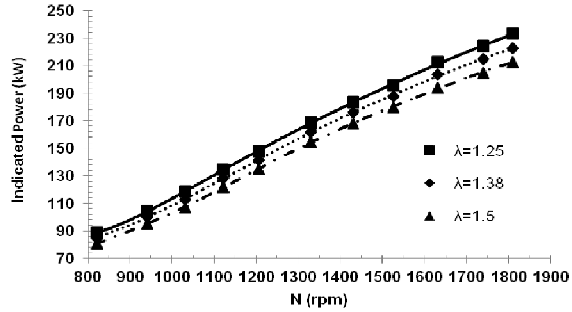

Figure 6. Variation of indicated power with engine speed at three different excess air ratios.

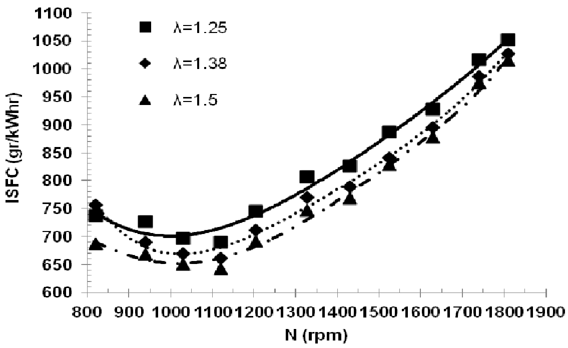

Figure 7. Variation of indicated specific fuel consumption (ISFC) with engine speed at three different excess air ratios.

At modes of 8 to 13, NOx emission decreased as excess air ratio increased. Comparing excess air ratio of 1.73 with 1.22, NOx emission decreased 74% at max engine speed and WOT i.e. mode 8 and 35% at WOT and engine speed of max brake torque i.e. mode 6. The reason is that burned gas temperature decreased as excess air ratio increased, considering that all of them were higher than 1.2. Higher air to fuel ratio results in lower combustion and burned gas temperatures. The lower temperatures attenuate N radical formation and lead to less NOx emissions. It is also found from Figure 8 that it is necessary to optimize spark timing and parts of the engine ignition system, in order to exploit lean mixture potential completely.

Figure 9 illustrates the engine brake power at two different excess air ratios under the test cycle. The power reduced as excess air ratio augmented due to lower fuel flow rate of the engine specially the max power reduced 23% as excess air ratio augmented from 1.22 to 1.29.

5. 3. Experimental Study of Waste Gate Opening Pressure Threshold Boost pressure ratio, charge air temperature at aftercooler exit, brake power, NOx emission and bsNOx at each 13 modes of steady state ECE-R49 standard test cycle and also total bsNOx are measured and calculated according to the measurements at four different opening pressure thresholds of waste gate as shown inFigure 10 to 15 respectively. InFigure 10 boost pressure ratio increases as waste gate opening pressure threshold increases and the increase is bigger at high loads and high speeds, i.e. modes 4 to 6 and 8 to 10, due to waste gate control parameter i.e. compressor outlet pressure.

Boost pressure ratio at max load (i.e. mode 6) increased 2, 3 and 8%, respectively for the pressure thresholds of 200, 265 and 323mmHg in comparison with 165 mmHg. The charge air temperature at aftercooler exit also increased with increasing waste gate opening pressure threshold as shown in Figure 11because of higher compressor work on charge air. The pressure threshold of 323 mmHg had considerably higher charge temperature than others. Brake power increased with increase of waste gate opening pressure threshold, as shown inFigure 12, due to higher boost pressure ratio and consequently higher air and fuel consumption.

Figure 13 illustrates experimental NOx emission at four pressure thresholds of waste gate opening under ECE-R49 test cycle for the engine. NOx emission was the highest at pressure threshold of 323 mmHg due to the considerably higher charge air temperature shown in Figure11that led to shorter time period of heat release because of higher flame speed and consequently higher combustion and burned gas temperatures. NOx emission increased 20% as the pressure threshold increased from 265 to 323 mmHg at engine speed of max brake torque and WOT operating condition (mode 6) due to the higher charge air temperature. The higher charge air temperature leads to higher combustion and burned gas temperatures that promote NOx formation according to Zeldovich mechanism.

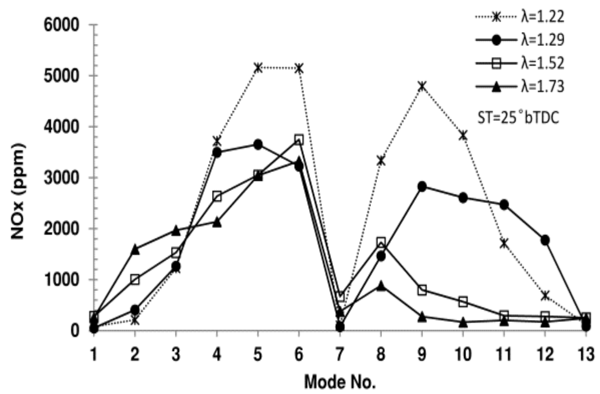

Figure 8. Variation of experimental NOx emission with 13 modes of ECE-R49 test cycle at four different excess air ratios.

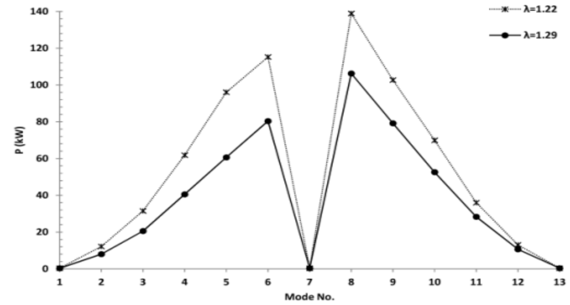

Figure 9 Variation of experimental brake power with 13 modes of ECE-R49 test cycle at four different excess air ratios.

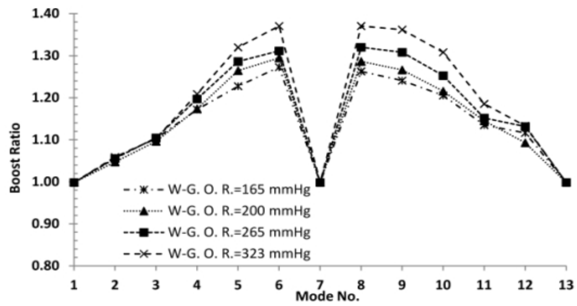

Figure 10. Variation of the engine boost pressure ratio with 13 modes of ECE-R49 test cycle for four different waste gate opening pressure thresholds (λ=1.193, ST=25° bTDC).

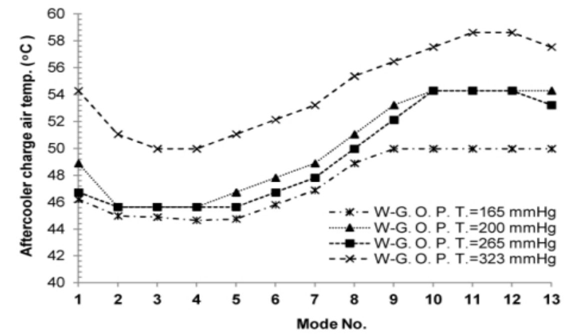

Figure 11. Variation of the engine charge air temperature with 13 modes of ECE-R49 test cycle for four different waste gate opening pressure thresholds (λ=1.193, ST=25° bTDC).

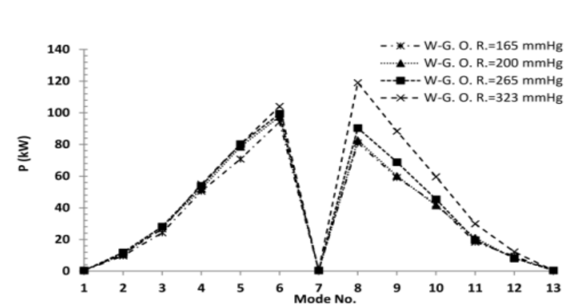

Figure 12. Variation of the engine brake power with 13 modes of ECE-R49 test cycle for four different waste gate opening pressure thresholds (λ=1.193, ST=25° bTDC).

Brake specific NOx, illustrated in Figure 14 under the test cycle, was the highest for waste gate opening pressure threshold of 323 mmHg due to the higher charge air temperature shown inFigure 11. Also, it is higher for waste gate opening pressure threshold of 165 mmHg in comparison with the pressure thresholds of 200 and 265 mmHg in most of the ECE-R49 modes due to lower brake power as shown inFigure 12. Brake specific NOx decreased 6 and 15% as the pressure threshold increased from 165 mmHg to 200 and 265 mmHg, respectively at the operating condition (mode 6) due to the greater brake power; it increased 22% as the pressure threshold increased from 265 to 323 mmHg at the operating condition (mode 6) due to the greater charge air temperature shown inFigure 11. The higher charge air temperature promotes the combustion and burned gas temperatures that provide high activation energy necessary for the first reaction of thermal mechanism.

Figure 15 compares total brake specific NOx emission of the engine for four waste gate opening pressure thresholds relatively based on the value of 323 mmHg. Total bsNOx of pressure thresholds of 200 and 265 mmHg decreased 6 and 12% respectively, in comparison with 165 mmHg due to higher brake power at higher pressure threshold, as shown inFigure 12. The emission parameter was the highest for the pressure threshold of 323 mmHg due to the considerably higher charge air temperature and consequently shorter time period of heat release that led to higher combustion and burned gas temperature and high NOx emission formation according to the thermal mechanism.Figure 15 also illustrates that waste gate opening pressure threshold of 265 mmHg is the optimum among the pressure thresholds tested.

Finally, higher waste gate opening pressure causes higher charge air temperature and higher brake power due to greater turbine and compressor work. These two effects have contradictory effects on bsNOx.

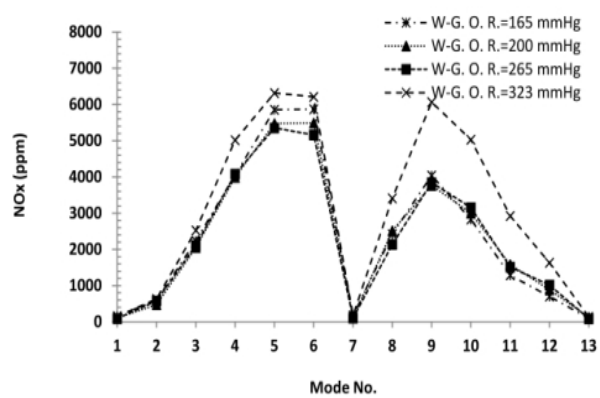

Figure 13. Variation of the engine NOx emission with 13 modes of ECE-R49 test cycle for four different waste gate opening pressure thresholds (λ=1.193, ST=25°bTDC).

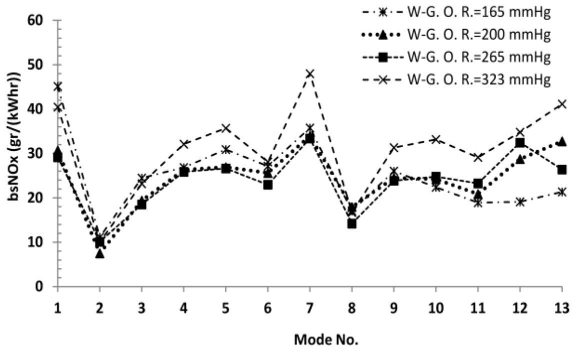

Figure 14. Variation of the engine brake specific NOx with 13 modes of ECE-R49 test cycle for four different waste gate opening pressure thresholds (λ=1.193, ST=25° bTDC).

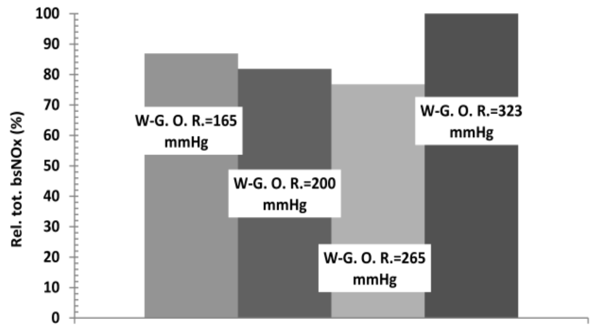

Figure 15. A comparison of experimental relative total bsNOx for four different waste gate opening pressure thresholds under ECE-R49 test cycle (λ=1.193, ST=25° bTDC).

Therefore, in order to minimize the bsNOx of the cycle i.e. total bsNOx, there is an optimum pressure threshold value for waste gate opening. Our findings also suggest that NOx emission considerably depends on charge air temperature.

6. CONCLUSIONS

NOx emission of turbocharged CNG engines is relatively high due to the fuel type and turbocharging that lead to high combustion and burned gas temperatures. The effects of excess air ratio on the engine indicated power and specific fuel consumption were numerically investigated at WOT by the code developed in the research. The effects of waste gate opening pressure threshold and excess air ratio were experimentally assessed on NOx emission and performance under 13-mode ECE-R49 test cycle. The following main conclusions were obtained:

1. It was found experimentally that increasing excess air ratio from 1.22 to 1.73 decreases NOx emission generally at the test cycle, specially 74% at WOT and max engine speed and 35% at WOT and engine speed of

max brake torque. Meanwhile, the engine power reduces at all modes of the cycle, in particular the max power reduces 23% as excess air ratio augments from 1.22 to 1.29.

2. Theoretical study indicated that the use of higher excess air ratio at a rate of 20% reduces indicated power and ISFC, specifically improves minimum ISFC by 7%. NOx emission of the engine at WOT increases as excess air ratio augmented from stoichiometric value up to NOx peak value at excess air ratio of 1.1 and then decreases.

3. Experiments revealed that boost pressure ratio and also brake power increases as waste gate opening pressure threshold augments. Both increases are bigger at high loads and high speeds because compressor outlet pressure is the waste gate controlling parameter. Boost pressure ratio at max load and its corresponding engine speed increases 2, 3 and 8%, respectively for the pressure thresholds of 200, 265 and 323mmHg in comparison with 165 mmHg.

4. Increasing waste gate opening pressure threshold augments the charge air temperature at aftercooler exit due to higher compressor work on the charge air.

5. It was experimentally found that under ECE-R49 test cycle, total bsNOx emission of 200 and 265 mmHg pressure thresholds decreases by 6 and 12% in comparison with 165 mmHg respectively due to higher brake power at the higher pressure threshold. This specific emission parameter is the highest for the pressure threshold of 323 mmHg due to the considerably higher combustion temperature. It was experimentally found that waste gate opening pressure threshold of 265 mmHg has the optimum value for total bsNOx of the cycle.

7. ACKNOWLEDGEMENTS

The authors acknowledge research assistants for their engineering support and also staff for their cooperation at the lab. Research vice-presidency of Sharif University of Technology is also acknowledged for their financial support.

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An Experimental and Theoretical Study of the Effects of Excess Air Ratio and Waste Gate Opening Pressure Threshold on Nox Emission and Performance in a Turbocharged CNG SI Engine

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P A P E R I N F O

Paper history:
Received 06 July 2014
Received in revised form 07 November 2014
Accepted 13November 2014

Keywords:
Turbocharged CNG SI Engine
NOx Emission
Performance
ECE-R49 Test Cycle
Excess Air Ratio
Waste Gated Turbocharger

چکیده

در این پژوهش، اثراتنسبت هوای اضافی و فشار آستانه بازشدگی دریچه هدرروی توربوشارژر بر آلایندگی NOx و عملکرد یک موتور گازسوز توربوچارجری بصورت تجربی در سیکل آزمون ۱۳ نقطه ای ECE-R49 ارزیابی می‌شوند. یک کد رایانه ای در محیط نرم افزار MATLAB ایجاد می‌شود تا NOx و عملکرد موتور را پیش‌بینی کند و نتایج آن با نتایج تجربی همین پژوهش ارزیابی می شوند. اثر نسبت هوای اضافی موتور بر آلایندگی NOx، توان و مصرف مخصوص سوخت اندیکاتوری بصورت مطالعه پارامتری به وسیله کد رایانه‌ای این پژوهش ارزیابی می‌شود. آلایندگی NOx بارکامل در نسبت هوای اضافی ۱/۱ بیشینه است. مطالعه پارامتری نشان می‌دهد که افزایش نسبت هوای اضافی به میزان ۲۰٪، توان اندیکاتوری بیشینه را ۹٪ کاهش و حداقل مصرف مخصوص سوخت اندیکاتوری را ۷٪ بهبود می‌دهد. نتایج آزمایش‌ها نشان می‌دهند که با افزایش فشار آستانه باز شدن دریچه هدررو، توان ترمزی موتور بخصوص در دور و بار زیاد، افزایش می‌یابد. به صورت آزمایشگاهی دریافته می‌شود آلایندگی NOx مخصوص ترمزی کل با تغییر فشار آستانه بازشدگی دریچه هدررو از ۱٦٥mmHg به ۲۰۰ و ۲٦٥mmHg، به ترتیب٦ و ۱۲٪ کاهش می‌یابند. افزایش این آستانه فشار به ۳۲۳mmHg، NOx مخصوص ترمزی کل را افزایش می دهد. در نتیجه، به منظور کمینه کردن NOx مخصوص ترمزی کل، فشار آستانه ۲٦٥mmHg، آستانه بهینه این موتور بین چهار حالت مورد آزمون می باشد.

.***doi***: *10.5829/idosi.ije.2015.28.02b.11*